LLNL-JRNL-493115

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August 12, 2011

American Institute of Physics Conference Proceedings

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Stellar and laboratory XUV/EUV line ratios in Fe XVIII and Fe XIX

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Abstract. A so-called XUV excess has been suspected with the relative fluxes of Fe XVIII and Fe XIX lines observed in the XUV and EUV ranges of the spectrum of the star *Capella* as observed by the *Chandra* spacecraft, even after correction for interstellar absorption. This excess becomes apparent in the comparison of the observations with simulations of stellar spectra obtained using collisional-radiative models that employ, for example, the Atomic Plasma Emission Code (APEC) or the Flexible Atomic Code (FAC). We have addressed this problem by laboratory studies using the Livermore electron beam ion trap (EBIT).

Keywords: X-ray spectra; Absolute and relative intensities; Effective temperatures
PACS: 32.30.Rj; 32.70.Fw; 97.10.Ri

INTRODUCTION

In typical stellar coronae under quiet conditions, the spectra of iron ions with an open $n = 3$ shell appear prominently in the VUV, EUV, and XUV ranges. At higher temperatures, especially in flares, the $n = 2$ shell is opened up as well. In such ions, electric-dipole forbidden transitions within the ground configuration give rise to VUV light with wavelengths near 1000 Å (VUV, energies near 10 eV), electric dipole transitions within the n=2 shell are associated with EUV transitions of wavelengths near 100 Å (EUV, energies near 100 eV), and $\Delta n > 0$ transitions have wavelengths near 10 Å (XUV, energies near 1000 eV) (see figure 1). All of these transitions are part of the same atomic system and its dynamics, and hence spectral modeling ought to be able to describe all of these parts similarly well. Assuming that synthetic spectra based on collisional-radiative models are correct and complete, observations of actual stellar spectra can then reveal properties and peculiarities of individual stars.

A multitude of observations by various spacecrafts (among them $XMM-Newton$ and *Chandra*) have addressed a few particularly bright stars such as $Capella$. The extensive calibration effort spent on the X-ray optics of the transmission grating spectrographs onboard these spacecrafts has made it possible to derive absolute flux data throughout the XUV and EUV ranges. Comparing the observations of $Capella$ with predictions made by the Astrophysical Plasma Emission Code (APEC), Desai et al. [1] find what they call an XUV/EUV excess of $Capella$. According to their analysis, Capella appears brighter (compared to APEC predictions) by a factor of 2 to 4 in the XUV than it does in the EUV. Such a finding would be very interesting, if it could be substantiated in physics terms. The effect of differential absorption in the interstellar medium is expected to play a minor role, amounting to only a few percent in this case [2, 3].

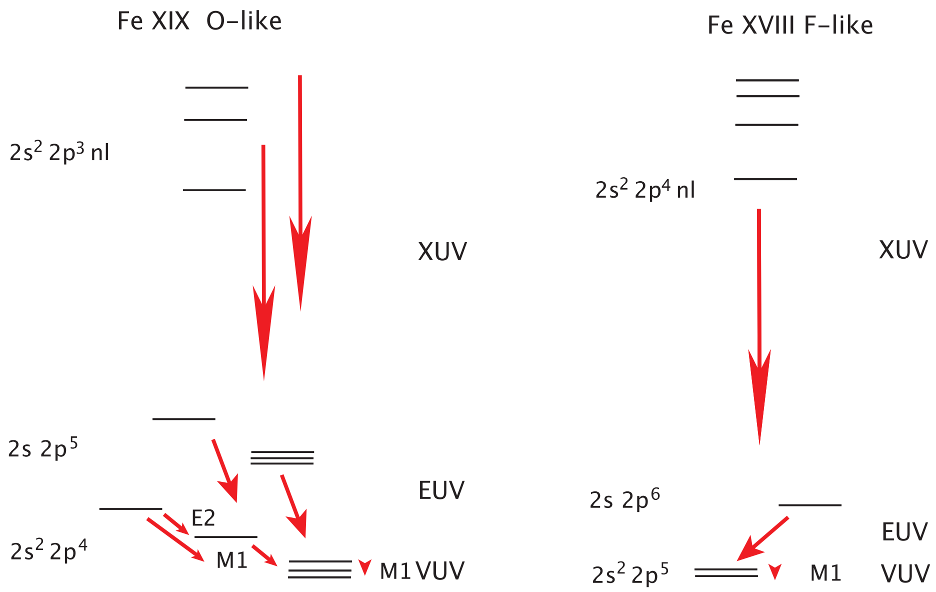

FIGURE 1. Simplified level schemes of Fe XVIII and Fe XIX and associated spectral ranges.

We have addressed this problem by laboratory studies using the Livermore EBIT-I electron beam ion trap, trying to find out whether the purported problem might be caused by insufficient knowledge of the atomic data or of the implementation of atomic processes in plasma modeling. Our understanding of the EBIT-I spectrum is founded on detailed Fe spectra that have mostly been obtained by Brown et al. [4] at the same facility. The spectrum of *Capella*, of course, contains lines from many other elements as well, and in the ranges of present interest, the discussion of the detailed identification is not finished yet [5]. The electron density of the exciting electron beam in EBIT-I can be adjusted in the range of about 10^{11} to 10^{13} cm^{-3}. This is lower than in a typical tokamak plasma and comparable to, but not the same as the density in energetic stellar flares. A quiet stellar corona has a somewhat lower density again. However, apparently EBIT is closest of all laboratory plasmas to the conditions in many astrophysical plasmas.

EXPERIMENT

In an electron beam ion trap, the quasi-monoenergetic electron beam of adjustable energy ionizes and excites particles in a volume defined by the potential differences among electric drift tubes. The ions are furthermore confined by a 3 T magnetic field that is provided by a pair of superconducting Helmholtz coils. The stepwise ionization process ends when the electron beam energy can no longer overcome the ionization potential of the highest charge state ions already produced. Hence the charge state distribution of the trapped ions can be varied with a defined upper limit. In our experiment, we have used electron beam energies between 1.4 and 2.0 keV, that is, from below the threshold for making the ions of interest (Fe^{17+}, Fe^{18+}) to optimum production without too much overionization. These excitation conditions differ significantly from the thermal exci-

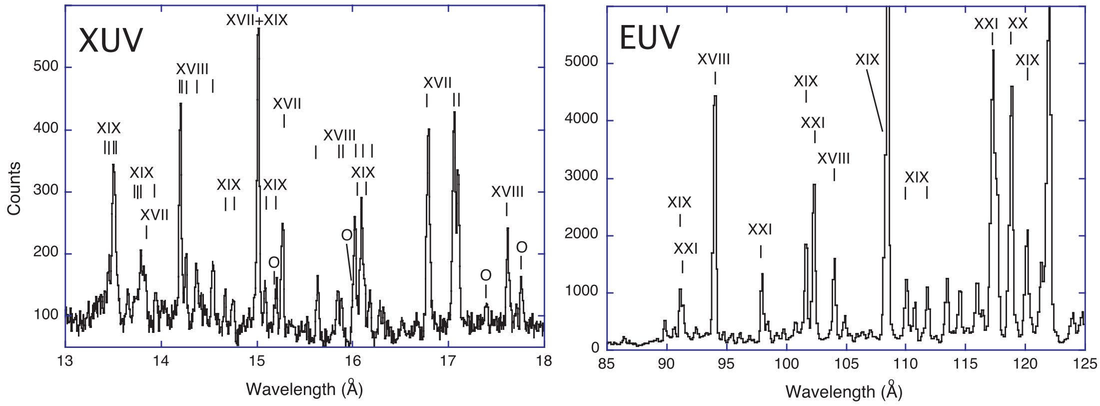

FIGURE 2. XUV and EUV spectra as observed at the LLNL EBIT with identification of selected iron lines by (Roman) spectrum number. Oxygen lines present result from the injection of Fe into EBIT as the gaseous compound ironpentacarbonyl.

tation in a stellar plasma which usually is described by a Maxwellian electron energy distribution; this difference had to be bridged by modeling (see below) for which we used the Flexible Atomic Code (FAC) [6].

The two spectral ranges were observed by flat-field spectrographs based on variable groove spacing gratings. For the EUV, we used an R = 5.6 m grating of 1200 ℓ/mm and a cryogenically cooled CCD camera, whereas for the XUV we used an R = 44.3 m grating of 2400 ℓ/mm and a microchannelplate (MCP) detector with position-sensitive readout [7, 8]. Sample spectra are shown in figure 2. The relative detection efficiency between the EUV (near 100 Å) and XUV (near 16 Å) ranges was determined on the basis of the calculated branching ratio of n = 1-3 and n = 2-3 transitions in the H-like spectrum O VIII. Inside the EUV range, the wavelength dependence of the grating efficiency of a flat-field diffraction grating similar to ours has previously been measured at a synchrotron light source [9]. In the XUV, the wavelength dependence of the detection efficiency relates to calculated line intensities along the 1s-np Rydberg series of O VIII.

DATA ANALYSIS

In order to produce the ions of interest, the electron beam was run at an energy near 2 keV, which is rather efficient for the excitation of the XUV spectrum, but much higher than the excitation energies of the EUV (and VUV) lines. Also, the electron density of the electron beam was in the 10^{12} cm^{-3} range, that is, two orders of magnitude higher than assumed for the radiant regions of *Capella*. The EUV and XUV spectra observed with such mono-energetic collisional excitation largely agree with the predictions by the FAC code for the same conditions. We conclude that the atomic data are adequate and that there are no gross mistakes in the theoretical treatment.

In order to compare our observations with those of *Capella*, we used FAC calculations to indicate the difference in line intensity between mono-energetic excitation and a Maxwellian plasma, assuming the accepted temperature of *Capella* (6 MK). The overall effect is a reduction of the XUV emissivities by a factor of 2.5 to 3 (as a function of level energy), whereas the EUV emissivities are hardly affected. By calculation, we also tested for the effects of electron density, and found the intensity of only a single EUV line to be density dependent.

In the XUV range the EBIT spectrum is rather complex, with about 80 spectral lines in the wavelength interval from 12 to 18 Å, most of which are weak and many are partly blended. The instruments onboard *Chandra* have a slightly higher spectral resolving power than our laboratory set-up, but the elemental abundance distribution contributes lines of other elements than Fe as well (see [5]). However, we find that overall the Fe spectra from both light sources pretty much agree with each other. EBIT evidently is an optically thin, collisional source, and hence we conclude the same for *Capella*, with no significant interstellar absorption disturbing the observation. The claimed XUV excess in relation to prediction appears to be an artifact of the collisional-radiative model used to describe the data.

The question arises whether one can identify the problem in the models that causes the claimed XUV excess by underpredicting the XUV emission. With the atomic data evidently correct and collision processes dominating, but density being unimportant, the only leftover free parameter is the temperature. Just like *Sun*, *Capella* as a coronal star is expected to show a temperature distribution throughout the various parts of the corona. Perhaps the accepted "representative" temperature of *Capella* needs to be revised. In our models, a temperature rise by some 15% significantly reduces the XUV excess. This suggests that the XUV emission is better described by a temperature that is correspondingly higher than the commonly used value inferred from distributed emission measure [10] determinations in the past.

ACKNOWLEDGMENTS

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and was supported by the NASA under work order NNH07AF81I issued by the APRA program. E.T. acknowledges support by Deutsche Forschungsgemeinschaft, Germany.

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